

## **Wind Retrieval using Marine Radars**

Jochen Horstmann  
NATO Undersea Research Center,  
Viale San Bartolomeo 400, 19126 La Spezia, Italy  
phone: (+39) 0187-527 381  
fax: (+39) 0187-527 354  
email: [Horstmann@nurc.nato.int](mailto:Horstmann@nurc.nato.int)

Award Number: N00101412WX20291  
<http://airsea.ucsd.edu/hires/>

### **LONG-TERM GOALS**

Within the High Resolution Air-Sea Interaction (HiRes) DRI the Center for Maritime Research and Experimentation (CMRE), former NATO Undersea Research Center, will develop and validate methodologies to retrieve wind field parameters from X-band marine radars. The main parameters are the mean surface wind vector; the high-resolution wind field, as well as wind gusts in vicinity of the measurement platform (within 2000 m). In contrast to traditional wind measurements marine radar retrieved winds are not influenced by the blockage and shadowing of the platform itself. Therefore, marine radars are expected to be an ideal solution to measure winds operationally from large platforms and ships. As the wind information is an important parameter in the marine radar wave measurement and the wave modeling, we anticipate that our radar retrieved wind information will help to improve the measuring and modeling activities of phase-resolved surface wave fields undertaken within HiRes.

### **OBJECTIVES**

The scientific objective is to develop a methodology to retrieve surface wind speed and direction using marine radar data acquired near grazing incidence at X-band with horizontal polarization in transmit and receive. In particular we aim at developing an algorithm that requires as little as possible calibration and straightforward calibration procedures. A further objective is to develop a methodology to detect and quantify wind gusts with marine radar imagery within 2 to 4 km of the platform, which aims toward a short time forecast of wind gusts/variability at the measurement platform. The validation as well as limitation of the developed methodologies will be investigated utilizing the measurements obtained during the HiRes experiment in June 2010 from RV Flip and RV Sproul.

### **APPROACH**

We have identified three artifacts in marine radar data, which are suited to infer the mean wind directions. For each of the artifacts we have developed methodologies to estimate the wind direction (for details see ONR annual report Horstmann, 2011). The artifacts are:

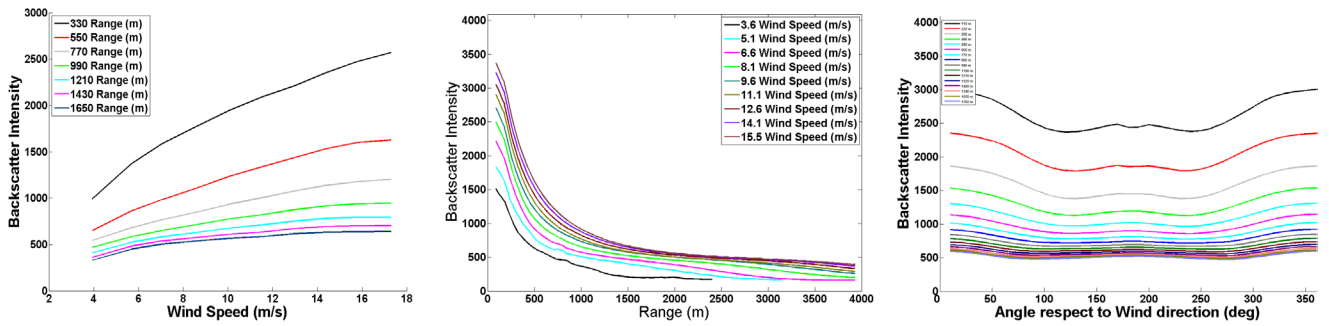
- Dependence of the mean NRCS on wind direction
- Streak like features visible in radar images resulting from integration in time (60 sec)

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2012</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2012 to 00-00-2012</b>	
4. TITLE AND SUBTITLE <b>Wind Retrieval using Marine Radars</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>NATO Undersea Research Center, Viale San Bartolomeo 400, 19126 La Spezia, Italy,</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>8</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

- Motion of backscatter patterns in image sequences from integrated radar data

The different methods for retrieving the wind directions from the above artifacts have been reported in Horstmann (2011) and enabled to retrieve a wind direction with an accuracy of less than  $10^\circ$  for most of the proposed techniques.

Wind speeds are retrieved from the mean radar backscatter intensity under consideration of the wind speed (Figure 1 left hand side). The relation of the dependence of the wind speed on wind direction and radar backscatter is given by a Geophysical Model Function (GMF), which has to be empirically estimated for every radar sensor. Using the GMF the mean wind speed of the radar can be estimated with a root mean square error of less than 0.6 m/s (Horstmann et al., 2011; Horstmann, 2011; Vicen-Bueno et al., 2012).



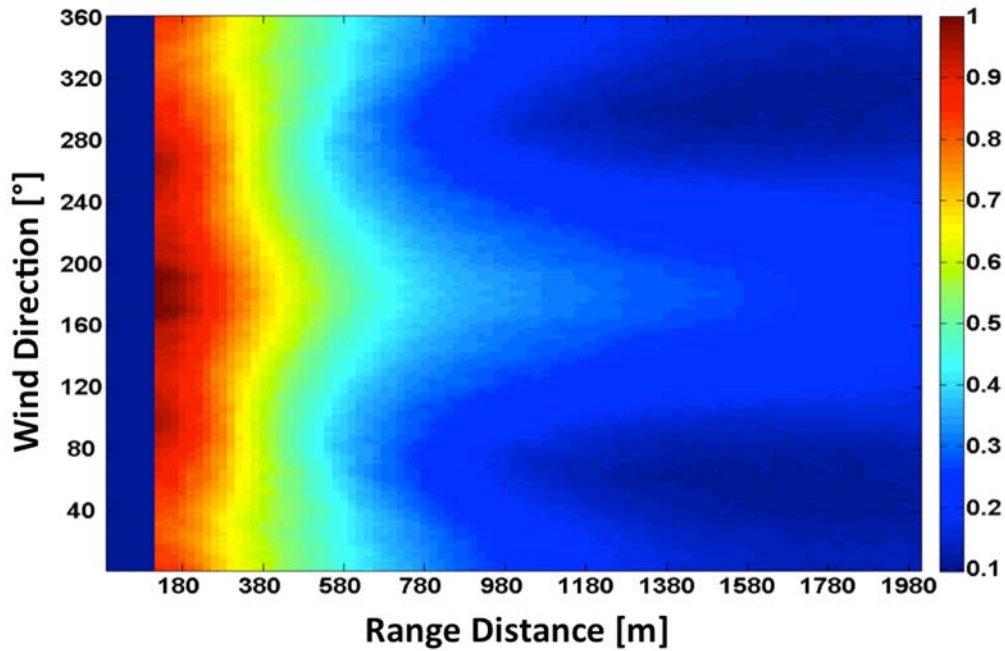
**Figure 1: Dependence of the marine radar retrieved normalized radar cross section (NRCS) on wind speed (left hand panel), range distance (center panel) and wind direction with respect to radar look direction (right hand panel). The radar data used to investigate the dependencies were collected during the HiRes experiment in June 2010 from the radar aboard RV Flip and the wind measurements from an Ultra Sonic Anemometer installed aboard RV Flip.**

For estimating wind variability as well as wind gusts we developed a methodology to retrieve the wind field in vicinity of the vessel (within a range of 2000 m) at a very high resolution in space and time (up to 20 m and 30 s). Figure 1 (left to right hand side) shows the strong dependencies of the NRCS on wind speed, range distance and wind direction resulting from the data collected during the HiRes experiment in June 2010 at the RV Flip. The reference winds in Figure 1 were measured at the RV Flip with an Ultra Sonic Anemometer and all winds were converted to a 10-minute mean. In general Figure 1 shows a strong increase of NRCS with wind speed, which significantly reduces with distance to the radar. Furthermore, there is a dependence on wind direction with a higher NRCS in upwind directions. These dependencies can be described by an empirical GMF. Prior to formulating the GMF we have investigated the sensitivity of the radar backscatter to the wind with respect to distance to the radar and wind direction with respect to antenna look direction. Therefore, the mean NRCS within a certain wind speed interval ( $\pm 0.5$  m/s) is computed at every range bin (20 m) and wind direction versus radar look direction bin ( $2^\circ$ ). From this 3D array we retrieve the gradient resulting in a 2D map of range and wind direction versus radar look, which gives an estimate of the change of NRCS on  $n$  wind speeds. The sensitivity  $S$  is a function of wind direction with respect to radar look direction  $\Phi$  and range distance  $r$  and is defined as:

$$S(\Phi, r) = \frac{\frac{1}{n-1} \sum_{i=1}^{n-1} |(I_{i+1}(\Phi, r) - I_i(\Phi, r)) / (u_{i+1}(\Phi, r) - u_i(\Phi, r))|}{\max \left( \frac{1}{n-1} \sum_{i=1}^{n-1} |(I_{i+1}(\Phi, r) - I_i(\Phi, r)) / (u_{i+1}(\Phi, r) - u_i(\Phi, r))| \right)}$$

Where  $I$  is the intensity of the radar backscatter and  $u$  the wind speed. The resulting sensitivity map is shown in Figure 2, where clear decreases of sensitivity with range distance can be observed as well as a higher sensitivity for up- and down wind directions compared to cross wind directions.

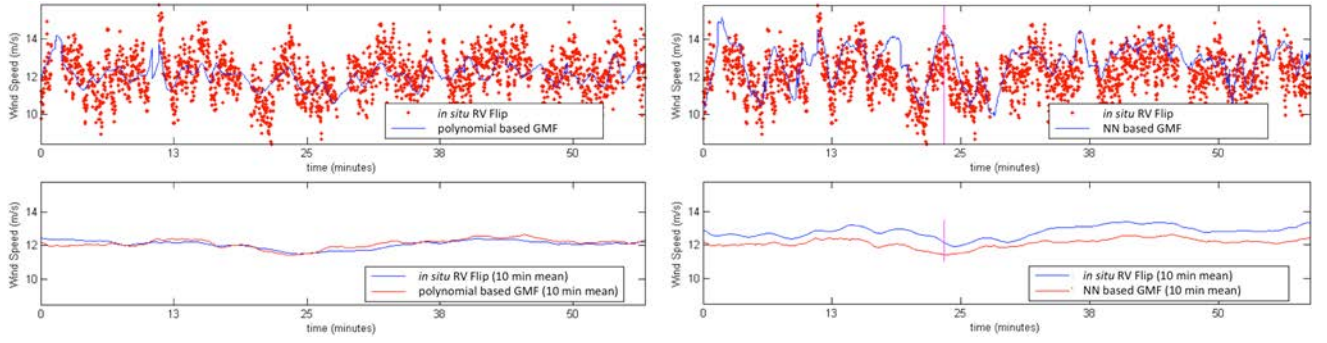
For the development of a suitable GMF we followed two empirical approaches, one is based on Neural Networks (NN) and the other on fitting a set of polynomial functions. Both resulting GMFs consider as input the mean NRCS of a small area over a short time period, the distance of that area to the radar as well as the mean wind direction of the area with respect to the radar look direction.



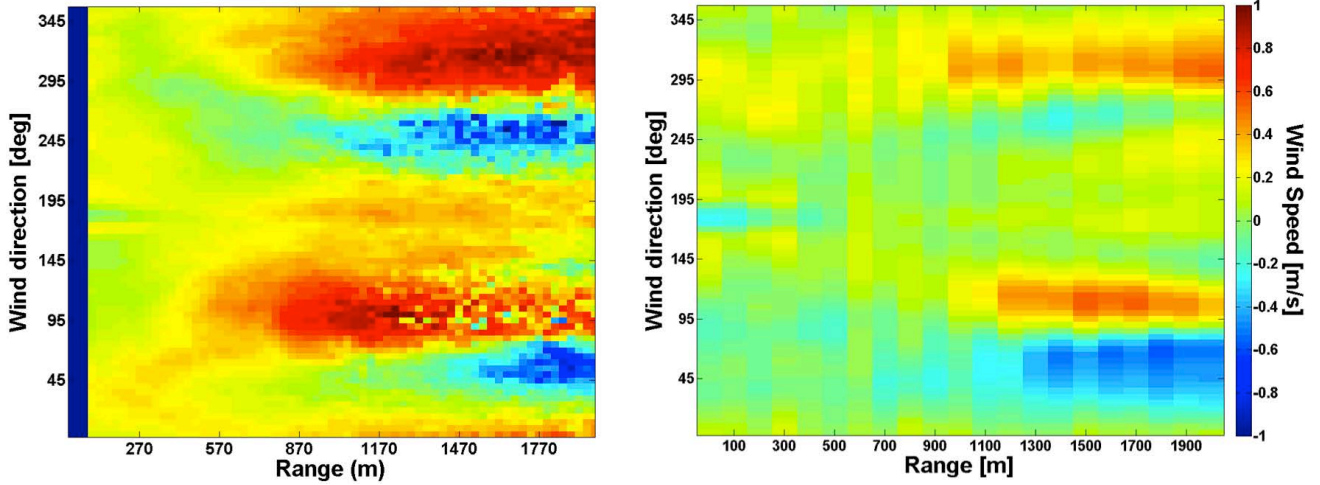
**Figure 2: Sensitivity of the marine radar backscatter to wind speed retrieval with respect to the range (distance to the radar) and wind direction with respect to the antenna look direction, where  $0^\circ$  is looking upwind and  $180^\circ$  is looking downwind.**

## WORK COMPLETED

In Figure 3 a time series of radar retrieved wind speeds of a grid point in a distance of 350 m in upwind direction is plotted in comparison to the *in situ* measurements. The radar retrieved wind speeds were computed by using the GMF developed with polynomial fits (left hand panel) and the GMF based on a NN (right hand panel). The upper panels in Figure 3 consider the *in situ* measured and radar retrieved wind speeds without averaging, while in the lower panel the measurements were averaged over 10 minutes. It can be seen that for this time series we obtain an excellent agreement between the radar retrieved wind speeds and the *in situ* measurements using either GMF.



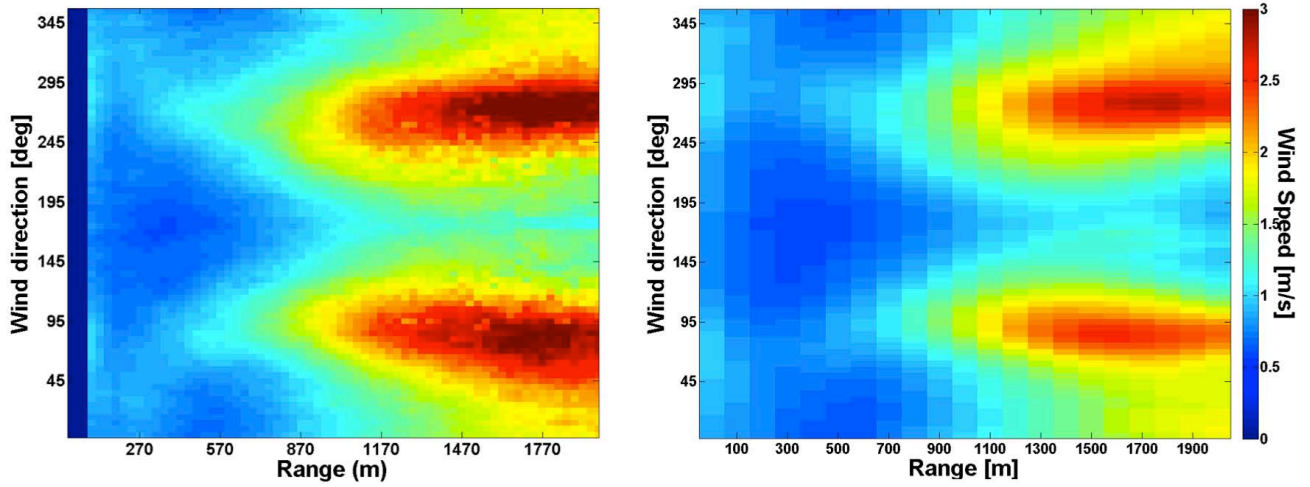
**Figure 3: Time series of marine radar retrieved wind speeds at a location 350 m upwind from the radar in comparison to in situ wind speeds collected at RV Flip. The upper plots are compared with full sampling of the in situ sensor and the marine radar and the lower plots show a 10 min mean of both measurements. On the left hand side are the wind speeds resulting from the Geophysical Model Function (GMF) based on the polynomial fits and on the right hand side from the Neural Network (NN) based GMF.**



**Figure 4: The bias in wind speed with respect to distance in range and wind direction. The left hand side depicts the bias resulting from the GMF based on polynomial fits and the right hand side the bias resulting from the NN retrieved GMF, respectively. The wind speeds were compared to the 10-minute mean wind speed collected at RV Flip.**

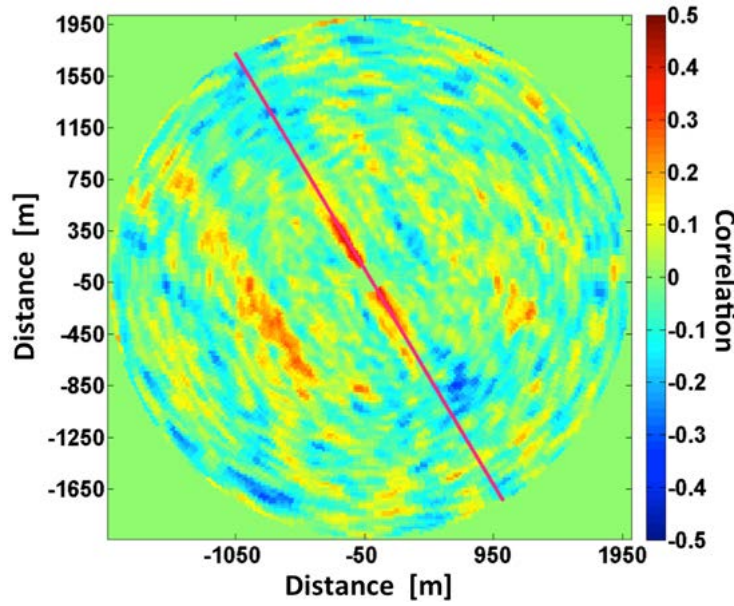
For validation of the marine radar retrieved wind speed field we compare each individual marine radar grid point to the 10 minute mean *in situ* wind speed measurements acquired at the RV Flip. This approach makes the assumption that the wind speed at the RV Flip represents the wind speed within the analyzing radius of the radar. Under this assumption the resulting bias with respect to range distance and wind direction with respect to radar look direction is plotted in Figure 4. Both GMFs show a similar behavior of the bias. The bias increases with range distance and has a clear wind direction dependence at larger ranges. The bias is significantly larger in case of the GMF fitted via polynomial functions (Fig 4 left hand side). However, in general the bias for the GMF fitted via polynomial functions is below 0.4 m/s for an distance of up to 850 m and in case of the GMF based on NN below 0.2 m/s for an distance of up to 1000 m (Fig 4 right hand side).



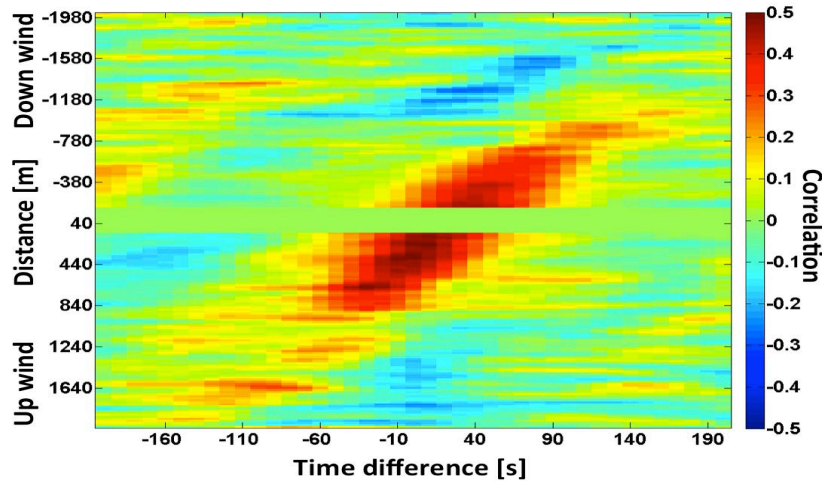


**Figure 5: The standard deviation in wind speed with respect to distance in range and wind direction. The left hand side depicts the standard deviation resulting from the GMF based on polynomial fits and the right hand side the bias resulting from the NN retrieved GMF, respectively. The wind speeds were compared to the 10-minute mean wind speed collected at RV Flip.**

The standard deviation of the wind speed is plotted in Figure 5. and shows for both GMF an increase with range distance in particular at cross wind directions. However, the error in wind speeds is below 1 m/s up to a range of 850 m. In general this strong increase of error at a certain range distance was expected from the sensitivity study. However, it should be noted that in the comparison we compared the wind speeds at the RV Flip to the radar measurements assuming homogenous wind speeds within the entire region, which does not represent the reality. The strong variation of the wind speeds in time and space can be seen in both the *in situ* as well as in the marine radar measurements. The better agreement of the wind speeds at RV Flip to radar measurements at up- and down wind locations is most likely caused by the temporal averaging of the wind measurements over 10 minutes, which results in considering an average along the up- down wind direction and not in cross wind.



**Figure 6: Correlation of every grid point from the radar retrieved wind field to the *in situ* measurement collected at RV Flip.**



**Figure 7: Correlation of wind speeds along a wind profile in wind direction (pink line in Figure 6) and the *in situ* wind speed recorded at RV Flip at different times.**

To investigate the airflow of the wind field we correlate the radar retrieved wind field to the *in situ* measurement collected at RV Flip. Figure 6 shows the resulting correlation. There is a high correlation along the wind direction (in this case approximately  $325^\circ$ ) in particular in vicinity of RV Flip. Furthermore, the correlation increases and decreases along up and down wind direction. The later behavior is expected as the wind gusts propagate in wind direction resulting in the variation of the wind speed. Investigating the correlation resulting from a wind profile in wind direction (pink line in Figure 6) and the *in situ* measurement at RV Flip over time shows the flow of the wind field along wind direction. As expected there is a higher correlation of the *in situ* wind speed in up wind direction

for wind fields acquired prior to the *in situ* measurement, which indicates the gust movement. The slope of the curve going through the highest correlations enables to estimate the mean flow of the gusts along wind direction.

## RESULTS

We have shown that marine radar backscatter imagery can be used to estimate the mean wind vector with an accuracy of less than  $7^\circ$  in wind direction and 0.5 m/s in wind speed (Horstmann, 2011; Lund et al., 2012), which are similar to the estimates of accurate *in situ* instruments. However, in contrast to *in situ* measurements, the radar measurements are not affected by their installation platform, which often induce blockage, shadowing and turbulence. Therefore, radar based wind measurements are better suited for measuring winds from large vessels or platforms.

In addition to single wind vector measurements we have extended the methodology to high-resolution wind field retrieval (20 m). This method enables to monitor the wind field in space and time with an error in wind speed below 1 m/s within a range of 850 m. The error in wind speed is larger for cross wind directions than for up- down wind directions. In case of up- down wind directions the wind speed estimates have an error below 1 m/s within a distance of approximately 1300 m and therefore allowing to detect extreme events at a great distance.

## IMPACT/APPLICATIONS

Due to the high accuracy of the mean radar retrieved surface wind measurements ( $7^\circ$  in direction and 0.5 m/s in speed) as well as due to the mentioned advantages of radar based wind measurements in comparison to standard *in situ* measurements, the methodology can be utilized for operational wind measurements in particular on large vessels. In addition the retrieval of high-resolution wind fields enables to monitor extreme events, such as strong wind gusts, which can be utilized as a warning system for wind sensitive operations.

The local wind situation is an important parameter in the marine radar wave measurement as well as wave modeling and we believe our radar retrieved wind field information will help to improve the measuring and modeling of phase-resolved surface wave fields.

## REFERENCES

- Horstmann, J., "Wind Retrieval using Marine Radars," *ONR Annual Report*, 7 pp., 2011.
- Horstmann, J., Raul Vicen-Bueno and Matthew Coffin, "Reading The Ocean With Marine Radars", *Defence Global*, pp. 58-60, may 2011.
- Lund, B., H.C. Graber, J. Horstmann and E. Terrill, "Ocean Surface Wind Retrieval from Stationary and Moving Platform Marine Radar Data", in *Proc. Geoscience and Remote Sensing Symposium*, p. 2790-2793, 2012.
- Vicen-Bueno, R., J. Horstmann, E. Terrill, T. de Paolo, and J. Dannenberg, "Real-Time Ocean Wind Vector Retrieval from Marine Radar Image Sequences Acquired at Grazing Angle", *Journal of Atmospheric and Oceanic Technology*, in press 2012.



## **PUBLICATIONS**

Vicen-Bueno, R., J. Horstmann, E. Terrill, T. de Paolo, and J. Dannenberg, Real-Time Ocean Wind Vector Retrieval from Marine Radar Image Sequences Acquired at Grazing Angle, *Journal of Atmospheric and Oceanic Technology*, in press 2012.

Horstmann, J., Raul Vicen-Bueno and Matthew Coffin, “Reading The Ocean With Marine Radars”, *Defence Global*, pp. 58-60, may 2011.